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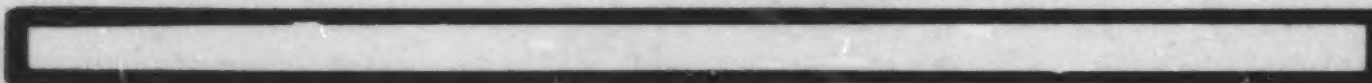
Comparison of Indices That Describe the Relationship between
Exposure to Ozone and Reduction in the Yield of Agricultural Crops

Boyce Thompson Inst. for Plant Research, Ithaca, NY

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A COMPARISON OF INDICES THAT DESCRIBE THE RELATIONSHIP BETWEEN EXPOSURE TO OZONE AND REDUCTION IN THE YIELD OF AGRICULTURAL CROPS

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Abstract—The objective of this study is to compare the use of several indices of exposure in describing the relationship between O_3 and reduction in agricultural crop yield. No attempt has been made to determine which exposure-response models best fit the data sets examined. Hourly mean O_3 concentration data, based on two-three measurements per hour, were used to develop indices of exposure from soybean and winter wheat experiments conducted in open-top chambers at the Boyce Thompson Institute, Ithaca, New York NCLAN field site. The comparative efficacy of cumulative indices (i.e. number of occurrences equal to or above specific hourly mean concentrations, sum of all hourly mean concentrations equal to or above a selected level, and the weighted sum of all hourly mean concentrations) and means calculated over an experimental period to describe the relationship between exposure to O_3 and reductions in the yield of agricultural crops was evaluated. None of the exposure indices consistently provided a best fit with the Weibull and linear models tested. The selection of the model appears to be important in determining the indices that best describe the relationship between exposure and response. The focus of selecting a model should be on fitting the data points as well as on adequately describing biological responses. The investigator should be careful to couple the model with data points derived from indices relevant to the length of exposure. While we have used a small number of data sets, our analysis indicates that exposure indices that weight peak concentrations differently than lower concentrations of an exposure regime can be used in the development of exposure-response functions. Because such indices may have merit from a regulatory perspective, we recommend that additional data sets be used in further analyses to explore the biological rationale for various indices of exposure and their use in exposure-response functions.

Key word index: Effect on crops, ozone, pollution indices.

INTRODUCTION

In 1980, the U.S. Environmental Protection Agency initiated the National Crop Loss Assessment Network (NCLAN) program, a coordinated program of field and laboratory studies, crop modelling, and economic investigations, to assess the economic significance of agricultural crop losses caused by air pollution (Heck *et al.*, 1984a). The program has focused primarily on understanding both the biological effects and economic consequences of the impact of O_3 on agricultural crops. The NCLAN program adopted a seasonal 7-h mean O_3 concentration (0900–1559 h) as the measure of exposure because (1) it was hypothesized that plants are most sensitive to O_3 during the period 0900–1559 h and (2) the concentration of O_3 is highest during this period.

Relationships between the seasonal 7-h mean and other indices of exposure have been assessed using monitoring data from the NCLAN studies (Heck *et al.*, 1984b). The analysis indicated that only the seasonal mean of the daily maximum 1-h concentration showed

a relatively consistent relationship with the seasonal 7-h mean. The relationships of the other exposure indices (i.e. the maximum 1-h and 7-h concentrations observed over a season) to the seasonal 7-h mean were less predictable, varying with exposure concentration, location and year. While NCLAN has used the seasonal 7-h mean in developing its exposure-response functions, the index would be difficult to enforce from a regulatory perspective. The long-term seasonal mean does not explicitly express O_3 exposure dynamics that occur over a seasonal period (Tingey, 1984; Lefohn and Tingey, 1985).

A biologically relevant exposure index that encompasses the dynamics of the exposure regime is difficult to establish. An index of exposure such as the seasonal 7-h O_3 mean weights all concentrations equally and can be reproduced by a variety of hourly distribution values. Conversely, an index such as the number of hourly occurrences equal to or above a minimum concentration computed over a season emphasizes peak exposures. Both indices, the seasonal and the number of occurrences equal to or above a

minimum concentration, are integrators of seasonal O_3 exposures that plants receive. However, neither index incorporates (1) the length of the episodic event nor the intervals between episodes, (2) the sensitivity of the target organism at the time of exposure, or (3) the amount of the pollutant that enters the target organism.

There is evidence that peak exposures are important in the response of vegetation to air pollutants. For agricultural crops, research results from both laboratory and field studies using acute, short-term exposures indicate that such exposures to O_3 appear to be more important than long-term, low concentration exposures (EPA, 1986).

Given the uncertainty regarding the relative importance of short-term, high concentration exposures and longer-term means in field exposures, an analysis and comparison of the performance of several exposure indices in exposure-response functions can provide information on the characteristics of the indices that are most important in predicting the response of a crop to O_3 . The objective of this study is to compare the use of several different types of indices in describing the relationship between O_3 exposure and reduction in agricultural crop yield. Because of the apparent importance of elevated concentrations and the lack of evidence that a threshold concentration exists for effects, we have created two indices that give greater weight to the higher concentrations than to the lower ones while still incorporating those lower concentrations that may contribute to effects on vegetation. Non-weighted exposure indices that use different threshold concentrations are also evaluated. The study also incorporates indices (i.e. 7-h mean concentrations) being considered by governmental regulatory agencies to protect vegetation from O_3 exposure.

MATERIALS AND METHODS

Crop yield and hourly O_3 monitoring data were obtained from NCLAN field studies conducted at the Boyce Thompson Institute for Plant Research in Ithaca, NY. The studies evaluated the effects of O_3 on soybean (*Glycine max* (L.) Merr. cv. 'Hodgson') in 1981 and on winter wheat (*Triticum aestivum* L. cv. 'Vonna') in 1982 and 1983 (Kohut *et al.*, 1986, 1987). All yields are reported as seed weight. In each study, the concentrations of O_3 in open-top chambers and ambient plots were monitored with a time-share system. The time-share monitoring system used Monitor Labs Model 8410 instruments in conjunction with Scanivalve automatic sequencing valves. Each instrument was used to monitor the concentrations of O_3 in 12 chambers. Each observation within a chamber lasted 2 min, and two-three measurements were obtained for a chamber each hour; hourly O_3 means were determined from these observations. The accuracy of using time-sharing systems to characterize 1-h and 7-h O_3 concentrations in NCLAN chambers and ambient plots has been investigated by Kohut and Heagle (1985) who reported that such systems accurately characterized the mean of the daily 7-h O_3 concentrations averaged over the experimental period. When two-three observation frequencies h^{-1} were used, the 1-h averages were almost identical to those determined by using 15-30 observations h^{-1} .

All sample lines were FEP Teflon and were continuously

aspirated with a vacuum pump to minimize loss of O_3 before the sample entered the monitor. Line losses were assessed at least twice during each field season and all monitors were subject to weekly zero and span checks. The experiments used four or five O_3 treatment levels in open-top chambers; each of the treatment levels was replicated. The O_3 treatment levels were produced using charcoal-filtered air, non-filtered ambient air, and additions of O_3 to non-filtered ambient air. Additions were made using both incremental (0.03, 0.06 and 0.09 ppm for soybean 1981 and winter wheat 1982) and proportional ($1.4 \times$ ambient and $1.8 \times$ ambient for winter wheat 1983) methods. Ambient air plots, not enclosed by open-top chambers, were used in each study to test for chamber effects. Crops were harvested at maturity, and yield was determined for each chamber and plot.

Ambient O_3 monitoring data were collected for the 24-h period for each day of the study (72 days in 1981, 71 days in 1982, and 36 days in 1983). Monitoring data for the chambers and ambient plots were recorded only during the 7-h exposure period. To calculate exposure indices that were based on the entire 24-h period, ambient O_3 monitoring data supplemented the 7 h within which O_3 additions to the chambers occurred. Missing values during the daily 7-h fumigation period indicated that additions of O_3 did not occur. These missing values were filled-in by using the ambient O_3 concentrations measured during the 24-h period. In the few instances when hourly O_3 concentrations were missing for both the chambers and ambient plots, a value of zero was used.

The air monitoring data sets associated with each chamber and ambient plot were used to calculate the following indices: (1) the mean of the daily 7-h (0900-1559 h EST) average concentrations calculated over the experimental period (7-h fixed); (2) the mean of the daily maximum 7-h average concentrations calculated over the experimental period (7-h variable); (3) the number of hourly concentrations ≥ 0.08 ppm; (4) the number of hourly concentrations ≥ 0.10 ppm; (5) the number of hourly concentrations ≥ 0.12 ppm; (6) the sum of all hourly concentrations ≥ 0.08 ppm (sum ≥ 0.08); (7) the sum of all hourly concentrations ≥ 0.10 ppm (sum ≥ 0.10); (8) the sum of all hourly concentrations ≥ 0.12 ppm (sum ≥ 0.12); (9) the sum of hourly concentrations where each concentration was weighted by a function that provided greater emphasis to the values above 0.08 ppm (W126); and (10) the sum of hourly concentrations where each concentration was weighted by a function that provided greater emphasis to the values above 0.10 ppm (W95). Twenty-four hours of O_3 concentrations were used to calculate all indices of exposure except for the 7-h fixed and 7-h variable indices. Exposure index values were calculated for each chamber and ambient air (AA) plots. In our study, the 7-h fixed and variable means are identified as 'experimental mean' indices, while the parameters calculated from (1) total number of hourly mean concentrations equal to or above a selected level, (2) the sum of all concentrations equal to or above a minimum level, and (3) the sum of all weighted concentrations are referred to as 'cumulative' indices of exposure.

In calculating the value of the index that gave greater weight to the elevated hourly mean O_3 concentrations, a weighting factor unique to the magnitude of the hourly mean concentration was multiplied by the hourly mean concentration itself. Summation of this product over all concentrations produced the index value. The weight assigned to each concentration was determined by a sigmoidal function. Lefohn and Runeckles (1987) have described the weighting function curve as

$$w_i = 1/[1 + M \times \exp(-A \times c_i)]$$

where

M and A are arbitrary constants,

w_i = weighting factor for concentration i , and

c_i = concentration i .

The arbitrary constants, M and A , were subjectively selected to give greater weight to the higher hourly mean concentrations of O_3 while still including the lower concentrations. The two weighting functions and their selected constants are shown in Fig. 1. The W126 function gives greater weight to the lower hourly concentrations of O_3 than does the W95 function (Fig. 1).

There were a total of 24 chambers and plots each in the 1981 soybean and in the 1982 winter wheat studies, and 48 chambers and plots in the 1983 winter wheat study. Using the indices of exposure and crop yield values for each of the individual open-top chambers and ambient plots, exposure-response functions were calculated. Linear and Weibull models were used to evaluate the performance of the exposure indices in the exposure-response functions. A non-linear estimation using the Quasi-Newton method was used to fit the data with a Weibull model. The Weibull model (Rawlings and Cure, 1985) is of the form

$$\text{yield} = \alpha \times \exp[-(\text{exposure index}/\sigma)^C]$$

where

α = the theoretical maximum yield at zero O_3 concentration,

σ = the O_3 exposure when the yield is 0.37α ,

C = a dimensionless shape parameter, and

exposure index = one of the exposure indices produced from the monitoring data.

The two criteria used to evaluate how well a model fitted the data were: (1) minimizing the residual mean square (RMS) in the Weibull model and (2) maximizing the coefficient of determination (R^2 , adjusted for the number of parameters in the model) in the linear model. The exposure-response functions that were developed differ from those previously published for 1981, 1982 and 1983 studies (Kohut *et al.*, 1986, 1987) because the present analysis (1) treated missing data differently, (2) included the ambient plots in the assessment, and (3) employed plot-level yields for all the crops.

Given an exposure-response model that adequately describes biological responses to air pollution, an exposure index that appears to fit that model well using a set of data for a specific year (e.g. 1982 or 1983 winter wheat) should also tend to fit that model reasonably well when data sets for the same crop and location are combined over several years (i.e. 1982 and 1983 winter wheat data). Accordingly, the yield and exposure data for the 1982 and 1983 (winter wheat) studies

were combined to compare the performance of the exposure indices.

The frequency distributions of the hourly O_3 concentrations were graphed and compared to distributions experienced at an agricultural site. The comparison provided an assessment of the degree to which the experimental O_3 exposure regimes simulated ambient conditions.

RESULTS

The means of the treatment-level crop yield and exposure index values for the three studies are presented in Table 1. The values of the 7-h fixed and 7-h variable indices were similar in the 1982 and 1983 experiments (Table 1). These experimental means did not reflect the differences in the O_3 peak exposures experienced in the 1982 and 1983 treatments. The number of hourly concentrations ≥ 0.08 ppm in the highest treatments (i.e. NF + 0.09) was greater than 300 in 1982, while less than 190 hourly O_3 concentrations ≥ 0.08 ppm were measured in the highest treatments (i.e. 1.8X) during the 1983 experiment. Differences between 1982 and 1983 in the number of hours equal to or above minimum concentrations (i.e. 0.08, 0.10 and 0.12 ppm) and the weighted exposure values (W126 and W95) were primarily the result of differences in the duration of the exposure periods for the 2 years (71 days in 1982 and 36 days in 1983). Differences in yield of wheat in non-fumigated plots in 1982 and 1983 were observed, indicating that other factors such as rainfall and temperature may have been influential.

Scatter diagrams presenting crop yield information as a function of several indices of exposure for the 1981 soybean and 1982 and 1983 winter wheat studies are presented in Figs 2, 3 and 4, respectively. For the experimental 7-h average index, the charcoal-filtered air treatments are nearest to the origin, the ambient plots and non-filtered air chambers are clustered together, and the O_3 addition treatments are located furthest away from the origin (increasing O_3 concentration). When the number of hours ≥ 0.08 ppm is used as an index, the charcoal-filtered, non-filtered and ambient air treatments are clustered near the origin since they experience few or no exposures to levels of O_3 greater than this threshold value. These treatments remain clustered near the origin when the W95 index is used because the function applies little weight to hourly concentrations less than 0.08 ppm. Accordingly, these treatments move further away from the origin when the W126 index is used since this index applies greater weight to hourly concentrations < 0.08 ppm than does the W95 index. The effects of exposures ≥ 0.08 ppm on the indices of exposure are evident in the 1983 winter wheat study (Fig. 4). While ambient levels of O_3 were higher, hourly O_3 concentrations ≥ 0.08 ppm occurred less frequently in all of the higher treatments when compared with the 1982 experiment. In this case, there are smaller differences in the plots produced with the ≥ 0.08 ppm, W126 and W95 indices of exposure (Figs 4b, 4c and 4d).

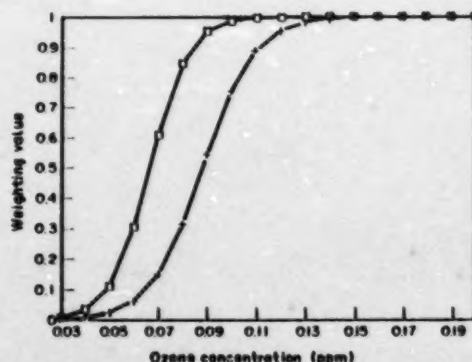


Fig. 1. Weighting functions used to calculate the W126 ($\square$) and W95 (+) integrated exposure values that used all hourly O_3 concentrations. The W126 weighting function is described by $w_i = 1/[1 + 4403 \times \exp(-126 \times C_i)]$ and W95 by $w_i = 1/[1 + 4403 \times \exp(-95 \times C_i)]$.

Table 1. Summarization of mean chamber values for each treatment for 1981, 1982 and 1983 Boyce Thompson Institute NCLAN experiments

Treatment	Number of chambers	Yield (kg ha ⁻¹)	7-h fixed (ppm)	7-h var. (ppm)	Number of occurrences ≥ 0.08 ≥ 0.10 ≥ 0.12	Sum ≥ 0.08 (ppm-h)	Sum ≥ 0.10 (ppm-h)	Sum ≥ 0.12 (ppm-h)	W126 (ppm-h)	W95 (ppm-h)
Soybean (1981)										
CF	4	2696	0.017	0.022	0	0.0	0.0	0.0	0.7	0.2
AA	4	2547	0.031	0.036	0	0.0	0.0	0.0	2.1	0.5
NF	4	2471	0.032	0.036	1	0.0	0.0	0.0	2.3	0.6
NF + 0.03	4	2092	0.047	0.049	16	1.3	0.1	0.0	8.3	2.4
NF + 0.06	4	1978	0.065	0.066	203	19.1	5.4	0.3	24.7	13.7
NF + 0.09	4	1476	0.091	0.092	328	40.4	36.8	26.2	42.3	37.7
Winter wheat (1982)										
CF	4	5328	0.021	0.028	0	0.0	0.0	0.0	1.2	0.3
AA	4	4048	0.044	0.049	6	0.5	0.0	0.0	7.5	1.9
NF	4	3572	0.042	0.048	5	0.5	0.2	0.2	6.6	1.8
NF + 0.03	4	2216	0.058	0.061	91	8.1	0.8	0.1	17.7	6.8
NF + 0.06	4	1696	0.076	0.078	252	26.5	17.0	5.9	32.8	22.2
NF + 0.09	4	1356	0.095	0.097	310	39.7	35.8	27.6	44.2	37.9
Winter wheat (1983)										
CF	8	4360	0.026	0.031	2	0.2	0.0	0.0	1.6	0.4
AA	8	3798	0.057	0.061	59	5.8	2.4	0.6	11.0	5.3
NF	12	3872	0.054	0.059	55	5.2	1.6	0.2	10.2	4.6
1.4X	8	2818	0.076	0.078	125	13.2	7.9	3.5	18.3	11.5
1.8X	12	2224	0.096	0.098	173	21.0	16.5	11.6	25.1	19.3

Actual values recorded in each chamber were used in the analysis.

CF = Charcoal Filtered; AA = Ambient Air; NF = Non-Filtered; NF + 0.03 = Non-Filtered + 0.030 ppm; NF + 0.06 = Non-Filtered + 0.060 ppm; NF + 0.09 = Non-Filtered + 0.090 ppm; 1.4X = 1.4 × Ambient; 1.8X = 1.8 × Ambient.

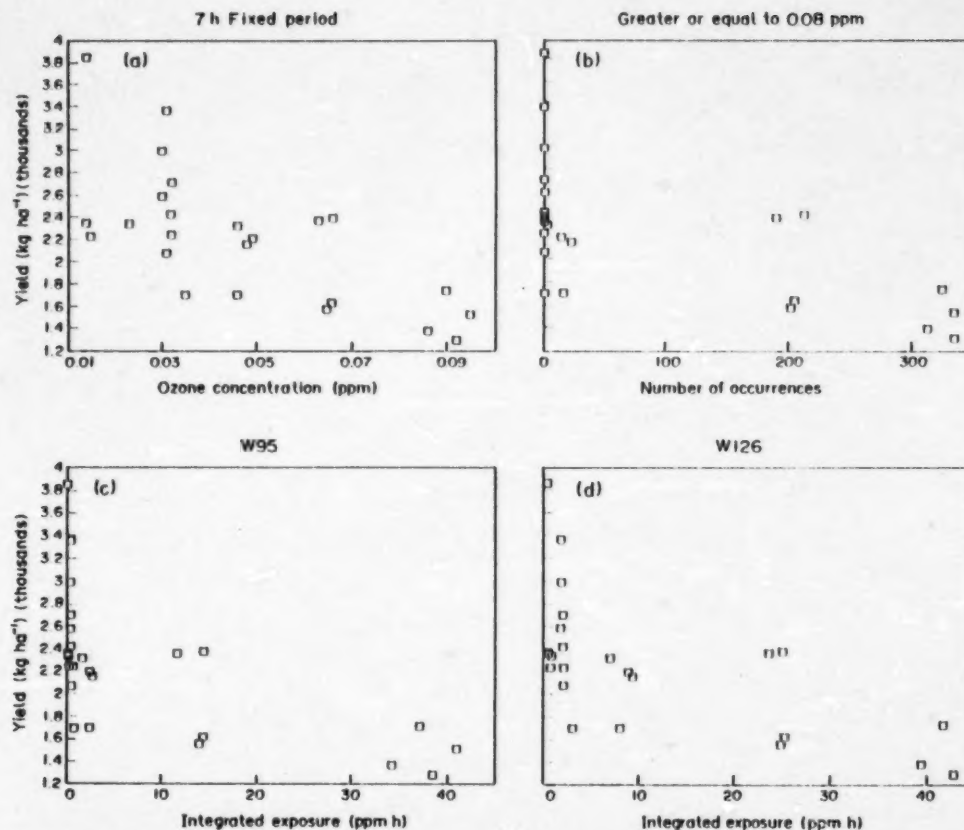


Fig. 2. Scatter diagram using 1981 soybean data from each chamber treatment showing yield (kg ha^{-1}) as a function of (a) 7-h fixed experimental mean; (b) number of occurrences ≥ 0.08 ppm; (c) W95 integrated exposure value; (d) W126 integrated exposure value.

The yield and exposure data for the 1982 and 1983 (winter wheat) studies were combined. The 7-h fixed indices for the 2-year period were plotted against yield (Fig. 5a). The chambers experiencing the highest treatment recorded similar values for the 7-h fixed indices but different yields (compare Fig. 3a with Fig. 4a). This is observed in the 0.09 and 0.10 ppm range. Figure 5b shows the yield as a function of number of occurrences ≥ 0.08 ppm. The number of hourly concentrations ≥ 0.08 ppm experienced in the 1982 experiments was over 300 (Fig. 3b) while the 1983 experiment had between 150 and 200 h ≥ 0.08 ppm (Fig. 4b). When the 1982 and 1983 data were combined, the figures showing yield as a function of the indices that emphasized the higher hourly O_3 concentrations (Figs 5b, 5c and 5d) did not exhibit clustering at the highest treatments as did the plot developed from the 7-h experimental mean index (Fig. 5a).

The frequency distributions of hourly O_3 concentrations for four of the treatments in the soybean study are presented (Fig. 6). Compared to the non-filtered treatment (Fig. 6a), the non-filtered + 0.03 ppm O_3 treatment shifted the curve to the right while maintain-

ing its lognormal-like distribution (Fig. 6b). The non-filtered + 0.06 ppm O_3 and non-filtered + 0.09 ppm O_3 treatments produced a bimodal distribution of concentrations (Figs 6c and 6d). The observed distribution of hourly mean concentrations when proportional additions were used in the 1983 study may also be bimodal, but are closer to what might be observed in rural areas (Figs 7 and 8).

The yield and exposure index data for the three studies were used with the Weibull and linear models to develop exposure-response functions. The Weibull model could only be fitted to the experimental 7-h fixed average, the experimental 7-h variable average, the number of occurrences ≥ 0.08 ppm, the sum of all hourly concentrations ≥ 0.08 ppm, and the W126 integrated exposure indices. The large number of exposure values near zero that were produced for the charcoal-filtered, ambient and non-filtered treatments using the other exposure indices may have precluded fitting the Weibull model.

The Weibull exposure-response functions are presented in Table 2. In most cases, the Weibull model tended to fit the data better with the sum of the

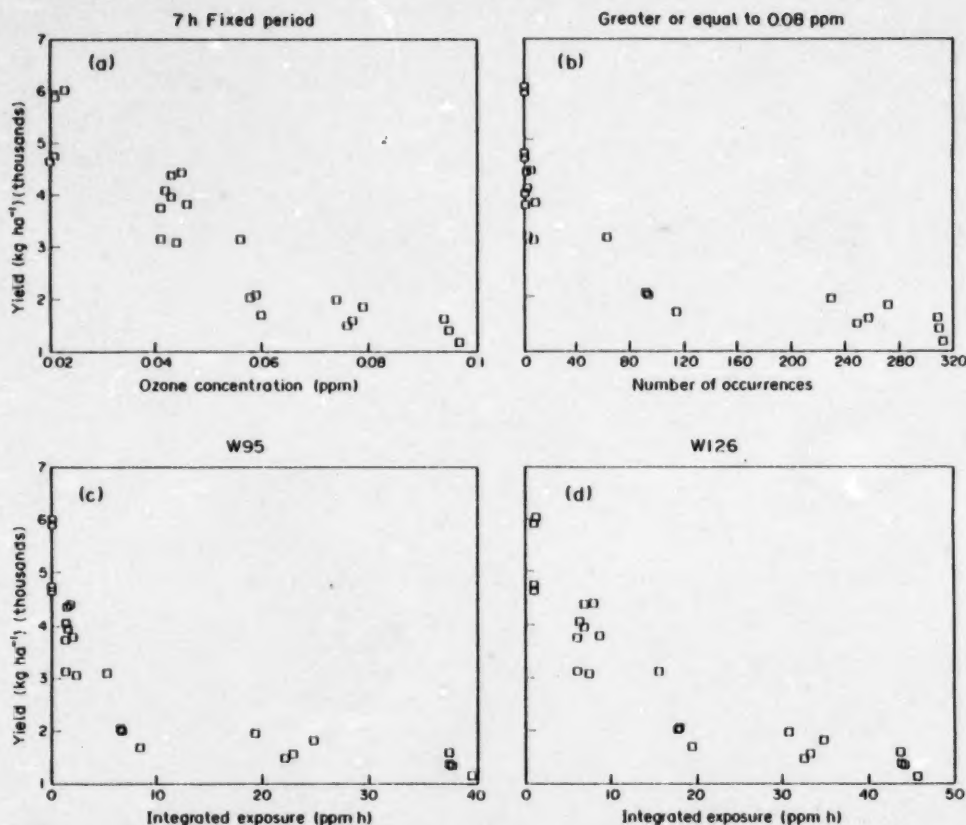


Fig. 3. Scatter diagram using 1982 winter wheat data from each chamber treatment showing yield (kg ha^{-1}) as a function of (a) 7-h fixed experimental mean; (b) number of occurrences ≥ 0.08 ppm; (c) W95 integrated exposure value; (d) W126 integrated exposure value.

weighted concentrations, the number of hourly concentrations ≥ 0.08 ppm, and the sum of all concentrations equal to or above 0.08 ppm than with the experimental mean indices. For the soybean study, the 7-h fixed, 7-h variable and W126 indices fitted the data equally well when the residual mean squares were compared. The model was unable to fit the W95 index. For the 1982 winter wheat data, the indices calculated using concentrations ≥ 0.08 ppm provided slightly better fits than did the W126 index or the 7-h averages. All six indices of exposure provided similar fits to one another using the 1983 winter wheat data. Fitting the combined 1982 and 1983 winter wheat data with a Weibull curve resulted in the weighted indices providing a slightly better fit than the indices using concentrations ≥ 0.08 ppm and a considerably better fit than the 7-h averages (Table 2).

The linear exposure-response functions produced with each of the ten exposure indices are listed in Table 3. The linear model showed no tendency to fit preferentially the data based on any of the indices. The

low coefficients of determination indicate that none of the indices of exposure provided a good linear fit to the 1981 soybean data. The 7-h fixed and 7-h variable experimental means and W126 indices of exposure provided similar fits to the linear model. Analysis of the 1982 winter wheat data indicated that the 7-h fixed and 7-h variable indices provided the best fit to the linear model, with the W126 index producing a slightly less suitable fit. While none of the exposure indices fitted the 1983 wheat data as well as they did the 1982 data, all of the indices produced similar coefficients of determination. When the 1982 and 1983 data were combined and used with a linear model, the number of occurrences ≥ 0.08 ppm and W126 indices provided higher coefficients of determination than the 7-h fixed or the 7-h variable indices. In all cases, the residuals were normally distributed, so although there was some evidence for heteroscedasticity, there was no reason to transform the data. All the regressions were highly significant, but the R^2 was lower in some cases than in others.

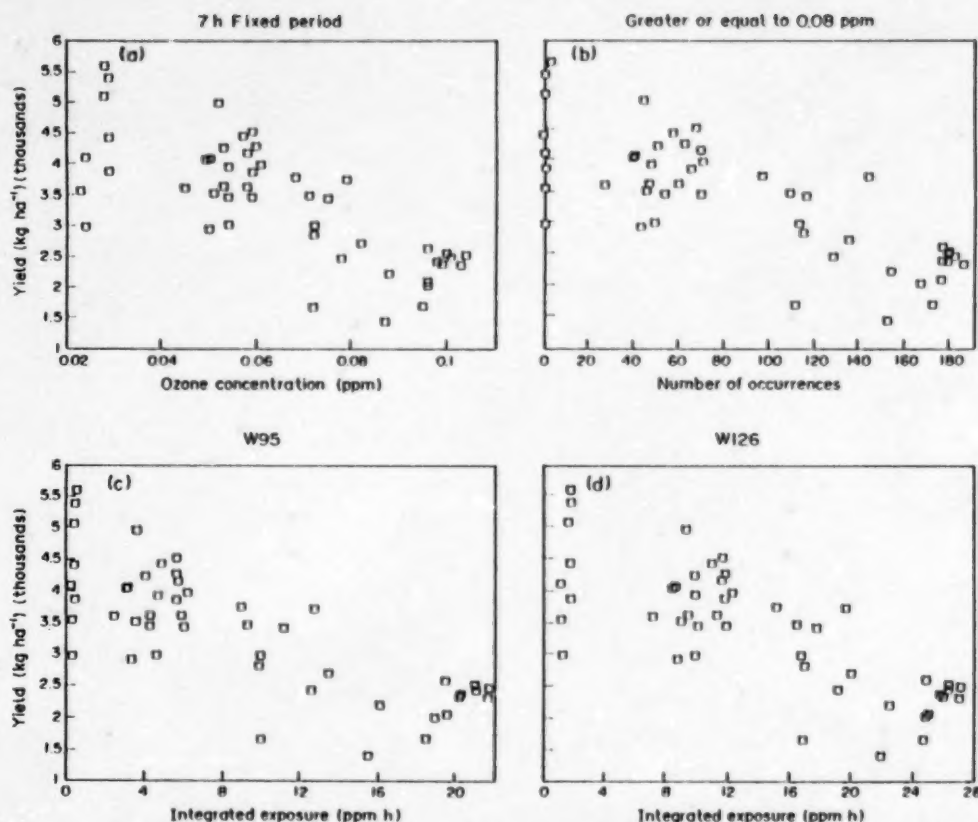


Fig. 4. Scatter diagram using 1983 winter wheat data from each chamber treatment showing yield (kg ha^{-1}) as a function of (a) 7-h fixed experimental mean; (b) number of occurrences ≥ 0.08 ppm; (c) W95 integrated exposure value; (d) W126 integrated exposure value.

DISCUSSION

Lefohn and Jones (1986) have described the lognormal-like frequency distributions of hourly O_3 concentrations that occur at several rural monitoring sites. The distribution patterns of hourly O_3 concentrations observed for the charcoal-filtered, non-filtered, and the non-filtered + 0.03 ppm O_3 treatments are similar to the patterns found at agricultural monitoring sites. However, the distributions of hourly concentrations of O_3 generated in the higher treatment chambers, using incremental additions, were bimodal and did not approximate those patterns commonly found at agricultural sites. Proportional additions of O_3 improve but do not completely eliminate the bimodal nature of the distributions. Large incremental or proportional O_3 additions to the chambers when the ambient O_3 concentrations are > 0.03 ppm cause the bimodal distributions.

Extensive field experiments to determine the relative importance of peak exposures have not been conducted; the definition of high and low O_3 concen-

trations is subjective. In our analysis, the hourly concentrations ≥ 0.08 , 0.10 and 0.12 ppm, have been arbitrarily defined as thresholds for high concentrations. However, because the lower concentrations might be responsible for eliciting part of the adverse effect, we also used the W126 and W95 weighted indices. When calculating indices for use in exposure-response functions, our results suggest that better fits may result if elevated O_3 concentrations receive greater weight than the lower concentrations. However, because the W126 index appeared to fit the data as well as or better than the W95 index, we believe the lower O_3 concentrations should be included when developing weighted exposure indices.

The 7-h experimental means in the highest treatments in 1982 and 1983 were based on 71 and 36 experimental days, respectively; the 7-h experimental means for the 2 years were similar. The experimental mean represents the average concentration over the experimental time period and is not necessarily sensitive to differences in the length of each experiment. On the other hand, the magnitude of the cumulative

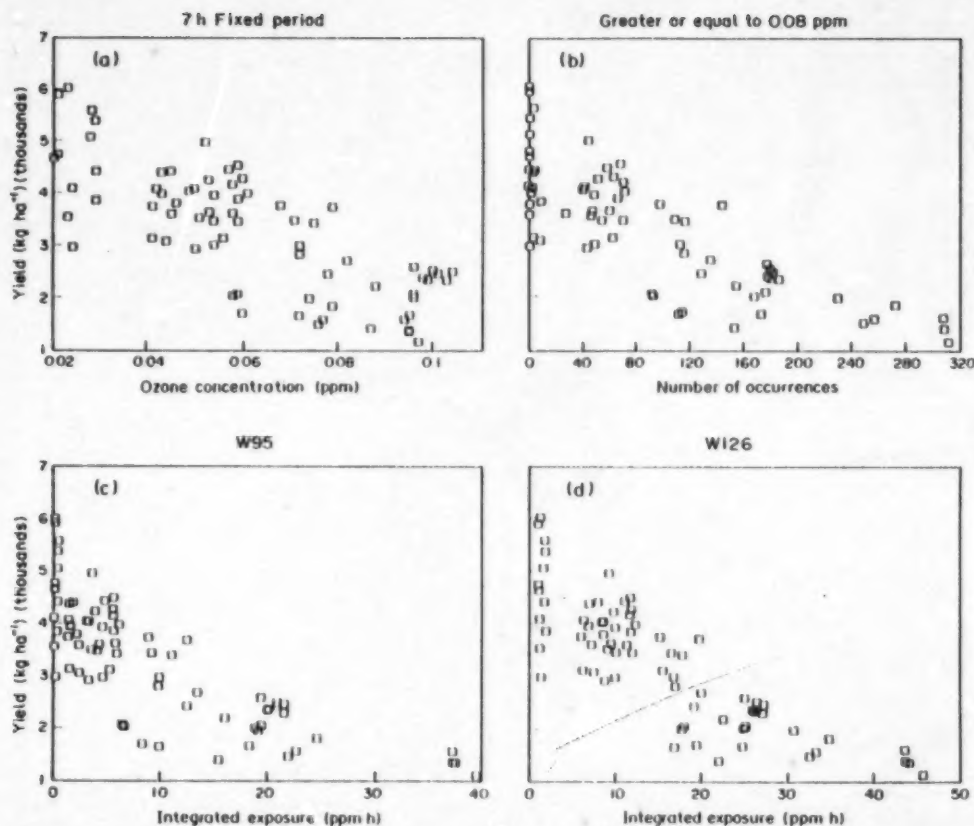


Fig. 5. Scatter diagram using combined 1982 and 1983 winter wheat data from each chamber treatment showing yield (kg ha^{-1}) as a function of (a) 7-h fixed experimental mean; (b) number of occurrences ≥ 0.08 ppm; (c) W95 integrated exposure value; (d) W126 integrated exposure value.

indices tends to increase as the length of the experiment increases. For the cumulative indices calculated in the 1982 and 1983 studies, the longer exposure interval in 1982 resulted in higher values than in 1983. Different winter wheat yields were observed for the 2 years (Table 1). Because the 7-h experimental means were similar for both years while the yields were different, the length of exposure appears to be an important consideration in selecting indices of exposure. Combining the 1982 and 1983 winter wheat data, we found that the exposure indices that emphasized the higher concentrations (i.e. W126 and number of occurrences ≥ 0.08) provided a better linear fit than the experimental mean indices. Using a Weibull curve, the data were fitted better using the W126 parameter than the two 7-h experimental mean indices of exposure.

Differences in climate and period of exposure may have played important roles in the yield of wheat in 1982 and 1983 and have not been considered in the present assessment. For example, the mean yield in the

charcoal-filtered treatments was lower when the 1983 study was compared to the 1982 experiment (Table 1). Precipitation in May and June 1983 was less than in 1982.

None of the exposure indices consistently provided a best fit with the two models tested. The selection of the model appears to be important in determining the indices that best describe the relationship between exposure and response. The focus of selecting a model should be on fitting the data points as well as on adequately describing biological responses. The investigator should be careful to couple the model with data points derived from indices relevant to the length of exposure.

Our analysis indicates that indices that weight higher concentrations within an exposure regime differently than lower concentrations (e.g. W126 and number of occurrences ≥ 0.08) can be used in the development of exposure-response functions. If these indices have biological significance, their use may be applicable to the standard setting process. The use of

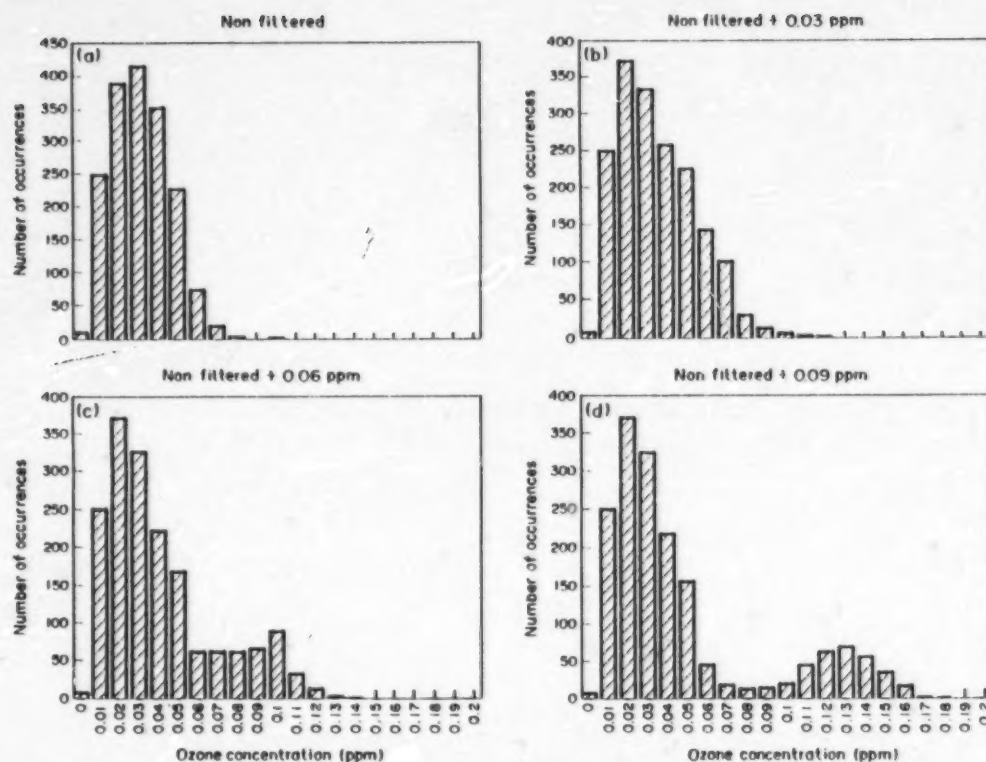


Fig. 6. Distribution pattern showing the number of hourly O_3 concentrations within specified ranges for the 1981 soybean incremental addition experiment for the (a) no filter; (b) no filter + 0.03 ppm; (c) no filter + 0.06 ppm; (d) no filter + 0.09 ppm treatments.

Table 2. Weibull exposure-response functions using various exposure statistics

	7-h fixed (ppm)	7-h var. (ppm)	No. of occur. ≥ 0.08	Sum ≥ 0.08 (ppm-h)	W126 (ppm-h)	W95 (ppm-h)
Soybean (1981)						
α (se)	3163 (874)	3393 (2277)	*	*	4194 (7897)	*
σ (se)	0.122 (0.028)	0.114 (0.046)	*	*	52.101 (446.769)	*
c (se)	1.032 (0.860)	0.981 (1.599)	*	*	0.205 (0.606)	*
†RMS (21)	213,726	217,602	*	*	216,654	*
Winter wheat (1982)						
α (se)	6809 (1314)	7722 (1868)	5317 (216)	5329 (215)	6452 (895)	*
σ (se)	0.061 (0.011)	0.059 (0.012)	139.007 (29.159)	14.472 (2.739)	19.350 (5.323)	*
c (se)	1.345 (0.426)	1.332 (0.431)	0.333 (0.045)	0.312 (0.038)	0.598 (0.149)	*
RMS (21)	305,873	314,910	202,577	193,519	254,693	*
Winter wheat (1983)						
α (se)	4489 (247)	4555 (288)	4308 (212)	4334 (211)	4374 (252)	4392 (195)
σ (se)	0.112 (0.008)	0.112 (0.006)	231.857 (25.082)	29.836 (4.184)	31.618 (3.068)	27.797 (3.235)
c (se)	2.448 (0.319)	2.555 (0.568)	1.503 (0.394)	1.179 (0.286)	1.749 (0.505)	1.079 (0.103)
RMS (45)	413,300	410,889	399,176	400,353	401,598	402,191
Winter wheat (1982/1983)						
α (se)	5319 (617)	5457 (523)	4414 (163)	4446 (181)	4817 (233)	4860 (356)
σ (se)	0.097 (0.008)	0.097 (0.007)	256.358 (27.247)	31.513 (3.950)	32.334 (2.503)	26.384 (3.723)
c (se)	1.506 (0.444)	1.585 (0.345)	1.063 (0.188)	0.865 (0.168)	1.118 (0.149)	0.682 (0.159)
RMS (69)	572,502	581,843	468,361	481,174	407,086	464,056

* Computer non-linear curve fitting procedure unable to adequately fit the Weibull curve to data.

† RMS (), Residual Mean Squares (degrees of freedom).

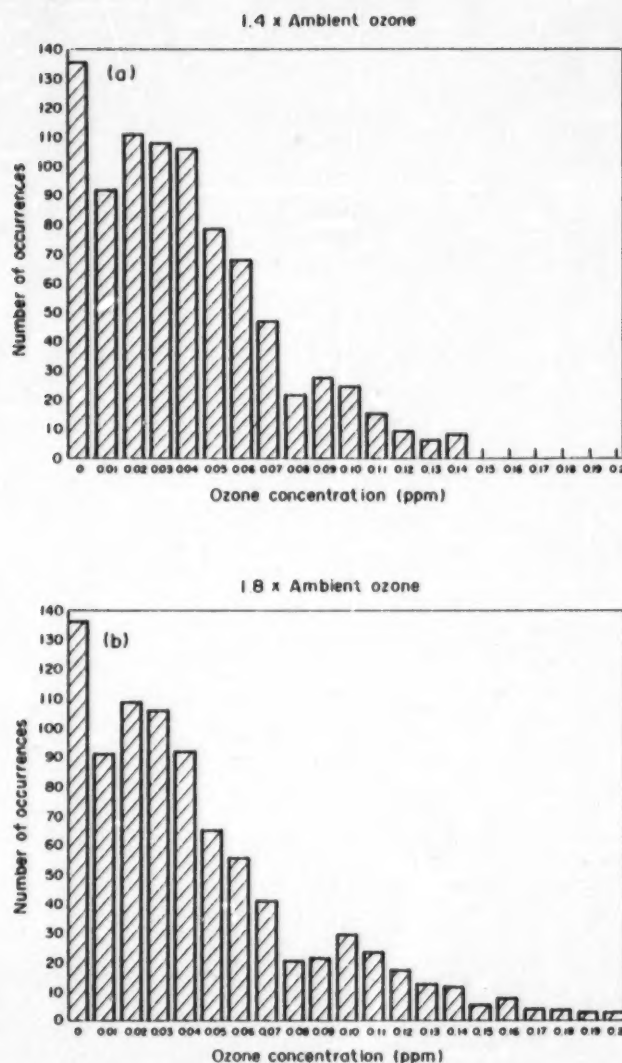


Fig. 7. Distribution pattern showing the number of hourly O₃ concentrations within specified ranges for the 1983 winter wheat proportional addition experiment for the (a) 1.4 x ambient air; (b) 1.8 x ambient air treatments.

such indices has been recommended by Lefohn and Runeckles (1987) for establishing air pollution standards. The cumulative indices (i.e. number of hourly occurrences equal to or above a selected minimum concentration, the sum of all hourly mean concentrations above a selected level, and the sum of weighted concentrations) can be calculated on a 'real time' basis; one can identify when a violation has occurred. If researchers can identify a specific cumulative index value that will protect selected vegetation, then it may be possible to employ it as an air quality standard. Ideally, however, care must be taken to consider not just exposure concentrations, but also the length of

exposure and the varying sensitivity of vegetation to air pollution (Lefohn and Jones, 1986; Krupa and Kickert, 1987).

In our analysis, we have used a small subset of data, and it is uncertain whether our results are representative. However, because cumulative indices may have considerable merit from a regulatory perspective, further efforts should be made to confirm that these indices can adequately be used in exposure-response functions.

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Table 3. Linear exposure-response functions describing the effect of O_3 exposures on $kg\ ha^{-1}$ yield of specific crops

	7-h fixed (ppm)	7-h var. (ppm)	Number of occurrences		Sum ≥ 0.08 (ppm-h)	Sum ≥ 0.10 (ppm-h)	Sum ≥ 0.12 (ppm-h)	W126 (ppm-h)	W95 (ppm-h)
Intercept (se)	3016 (200)	3115 (224)	Soybean (1981)		2462 (121)	2393 (118)	2355 (119)	2558 (129)	2464 (121)
Slope (se)	-17,029 (3750)	-18,003 (4048)	2401 (118)		-24,79 (6.61)	-25,99 (7.75)	-32,86 (10.97)	-25,99 (6.33)	27,71 (7.35)
R^2	0.484	0.473	-3,36 (0.99)		0.390	0.338	0.290	0.434	0.392
			0.347		0.291				
Intercept (se)	6158 (322)	6575 (371)	Winter wheat (1982)		4010 (237)	3724 (266)	3543 (282)	4568 (231)	4025 (253)
Slope (se)	-55,377 (5246)	-58,994 (5788)	3761 (263)		-77,69 (11.98)	-76,75 (16.43)	-89,78 (24.42)	-83,54 (9.65)	-83,59 (13.88)
R^2	0.835	0.825	-10,28 (2.11)		0.656	0.498	0.381	0.773	0.622
			0.520						
Intercept (se)	5357 (270)	5559 (293)	Winter wheat (1983)		4320 (146)	4053 (130)	3879 (123)	4651 (182)	4312 (147)
Slope (se)	-31,119 (3942)	-32,608 (4104)	4103 (132)		-98,98 (11.79)	-111,57 (14.23)	-143,75 (20.00)	-92,62 (11.26)	-108,02 (12.99)
R^2	0.575	0.578	-15,22 (1.91)		0.605	0.572	0.259	0.596	0.600
			0.581						
Intercept (se)	5558 (242)	5802 (268)	Winter wheat (1982/1983)		4160 (120)	3884 (121)	3716 (123)	4582 (132)	4158 (124)
Slope (se)	-37,455 (3658)	-39,247 (3885)	3918 (121)		-85,30 (7.84)	-88,70 (10.14)	-108,36 (14.77)	-86,36 (6.89)	-92,24 (8.84)
R^2	0.600	0.593	-11,89 (1.32)		0.629	0.522	0.435	0.692	0.609
			0.536						

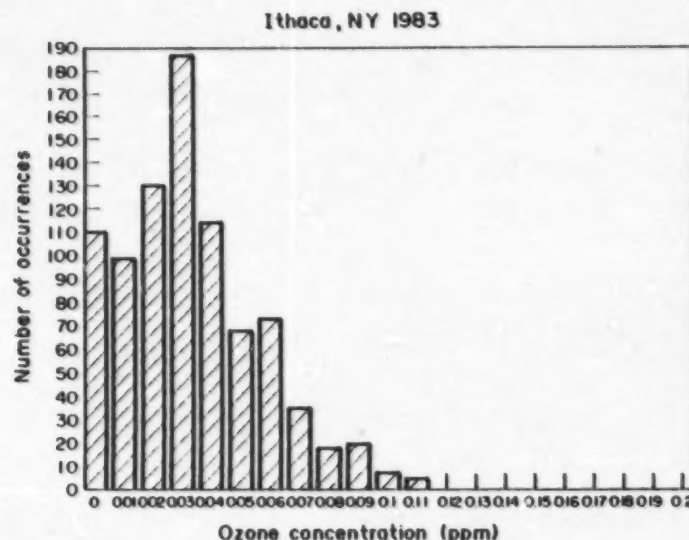


Fig. 8. Distribution pattern showing the number of hourly O₃ concentrations within specified ranges for Ithaca, NY, a site located in an agricultural area, for 1983.

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REFERENCES

- Heck W. W., Cure W. W., Rawlings J. O., Zaragoza L. J., Heagle A. S., Heggstad H. E., Kohut R. J., Kress L. W. and Temple P. J. (1984a) Assessing impacts of ozone on agricultural crops - I. Overview. *J. Air Pollut. Control Ass.* 34, 729-735.
- Heck W. W., Cure W. W., Rawlings J. O., Zaragoza L. J., Heagle A. S., Heggstad H. E., Kohut R. J., Kress L. W. and Temple P. J. (1984b) Assessing impacts of ozone on agricultural crops - II. Crop yield functions and alternative exposure statistics. *J. Air Pollut. Control Ass.* 34, 810-817.
- Kohut R. J., Amundson R. G. and Laurence J. A. (1986) Evaluation of growth and yield of soybean exposed to ozone in the field. *Envir. Pollut. (Series A)* 41, 219-234.
- Kohut R. J., Amundson R. G., Laurence J. A., Colavito L., van Leuken P. and King P. (1987) Effects of ozone and sulfur dioxide on the yield of winter wheat. *Phytopathology* 77, 71-74.
- Kohut R. J. and Heagle A. S. (1985) Assessment of the importance of observation frequency in time-sharing monitoring systems for O₃. In *National Crop Loss Assessment Network (NCLAN) 1983 Annual Report*, pp. 162-173. Corvallis, OR, EPA-600/3-85-061.
- Krupa S. and Kickert R. N. (1987) An analysis of numerical models of air pollutant exposure and vegetation response. *Envir. Pollut.* 44, 127-158.
- Lefohn A. S. and Jones C. K. (1986) The characterization of ozone and sulfur dioxide air quality data for assessing possible vegetation effects. *J. Air Pollut. Control Ass.* 36, 1123-1129.
- Lefohn A. S. and Runeckles V. C. (1987) Establishing standards to protect vegetation - ozone exposure/dose considerations. *Atmospheric Environment* 21, 561-568.
- Lefohn A. S. and Tingey D. T. (1985) Comments on injury response of *Phaseolus vulgaris* to ozone flux density. *Atmospheric Environment* 19, 206-208.
- Rawlings J. O. and Cure W. W. (1985) The Weibull function as a dose response model to describe ozone effects on crop yields. *Crop Sci.* 25, 807-814.
- Tingey D. T. (1984) The effects of ozone on plants in the United States. In *Proc. International Workshop on the Evaluation of the Effects of Photochemical Oxidants on Human Health, Agricultural Crops, Forestry, Materials and Visibility* (edited by Grennfelt P.), pp. 60-71. Swedish Environmental Research Institute, Göteborg, Sweden.
- U.S. Environmental Protection Agency (1986) Air Quality Criteria for Ozone and Other Photochemical Oxidants, Vol. 3. Environmental Criteria and Assessment Office, Research Triangle Park, North Carolina. EPA/600/8-84/020cF.